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A New Microcomputer-Based ECG Analysis System

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Summary: A new automated ECG system using advances in microprocessor technology and computerized electrocardiography is described. This microcomputer-based system is self-contained and mobile. It acquires both the 12-lead and orthogonal lead (Frank) electrocardiograms and analyzes the latter within minutes. Software includes the program developed in the Veterans Administration which uses advanced statistical classification techniques and a large well-documented patient data base. Diagnostic probabilities are computed using a Bayesian approach. Diagnostic performance has been tested using independent clinical criteria and found to be quite accurate. This system enables the clinician to immediately review the computer's identifications, measurements, and diagnostic classifications and quickly use these results in clinical decision making. Serial comparisons are readily made since all previous recordings are stored on floppy diskettes. The use of microprocessors in this system makes it economically feasible for practicing physicians.

Key words: electrocardiography, microcomputers, computer-assisted diagnosis, cardiovascular diagnosis, Bayes' theorem, probability, computers

Introduction

A new ECG system which combines the most advanced ECG diagnostic software with hardware based on a microcomputer has now become available for clinical use. Software which has taken many years of research and much manpower to develop (Cornfield *et al.*, 1973; Klingeman and Pipberger, 1967, 1970) has been incorporated into this system that is small, self-contained, and relatively inexpensive. It can be utilized as a powerful tool in a doctor's office as well as a clinic or hospital.

This system is a product of the vast amount of experience accumulated in the Veterans Administration studies on computer analysis of electrocardiograms which began in the late 1950s. The software, which includes the computer program developed in the Veterans Administration, uses advanced statistical techniques and the large, well-documented data base accumulated over many years. The hardware for the new system is microcomputer based and represents a genuine advance in hardware design for ECG processing.

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* The ECG system was conceived by Jack Klingeman, who since 1965, has specialized in diagnostic techniques for noninvasive evaluation of cardiovascular disease. In cooperation with the other authors he implemented the system and began demonstrating its usefulness to the medical community. He completed the initial manuscript describing the system shortly before his death on July 27, 1982.

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Materials and Methods

Equipment and Software

ECGs are acquired and analyzed in minutes using a microcomputer-based system (Fig. 1). This self-contained, mobile system is built around a Digital Equipment Corporation computer, the MINC (either the MINC-11 or MINC-23 can be used). It is on wheels and can be moved to the patient's bedside. The MINC contains from 32,000 to 128,000 words of 16-bit memory, a 12-bit analog-to-digital converter, a clock, an isolation transformer, a videographing terminal, and two floppy diskette drives with a capacity of approximately one-half million bytes per diskette. One diskette contains the system software and ECG program and the other is used for storage of patient data. A graphics printer can be attached to the system to provide a hard copy of the current video display of the terminal at any time. In addition to this equipment the ECG system contains a module with patient signal conditioning amplifiers having bandwidths of 0.05–250 Hz. This module, which was designed and built especially for this system, makes it possible to record both the 12-lead and orthogonal lead ECGs and transmit them directly from the patient to the computer while providing complete electrical isolation. The ECG module plugs into a single-quad height slot of the MINC in the same manner as other MINC input/output modules. (Another module is also available for use with this system which provides for fully automated systolic time interval analysis (Kyle *et al.*, 1980)). This module was designed and built to be easy to use, dependable, and to provide accurate results.

The software is based on the computer program developed in the Veterans Administration. It uses the Bayesian approach to diagnostic classification combining multivariate techniques with statistics from the large, well-documented data base accumulated over many years. The program for wave recognition and diagnostic classification has been extensively tested against independent evidence of diagnosis.

Recording Procedure

The patient's diskette is placed in one of the diskette drives. The patient's information is entered through the keyboard in response to requests for information specified on the videographing terminal. The name and identifying number are entered first. Additional information such as the date, blood pressure, age, race, and sex are then entered in response to the prompts. A list of broad diagnostic categories (Table I) is then displayed for entry of prior information known about the patient. A special set of prior probabilities (priors) will be used in the diagnostic classification procedure depending on the choice. If two categories are selected a set of priors for the combination will be used.

The 12-lead and Frank orthogonal lead (XYZ) ECGs are recorded with a standard Marquette Electronics, Inc. patient cable. Sets of 3 simultaneous leads are automatically switched under software control as follows: I

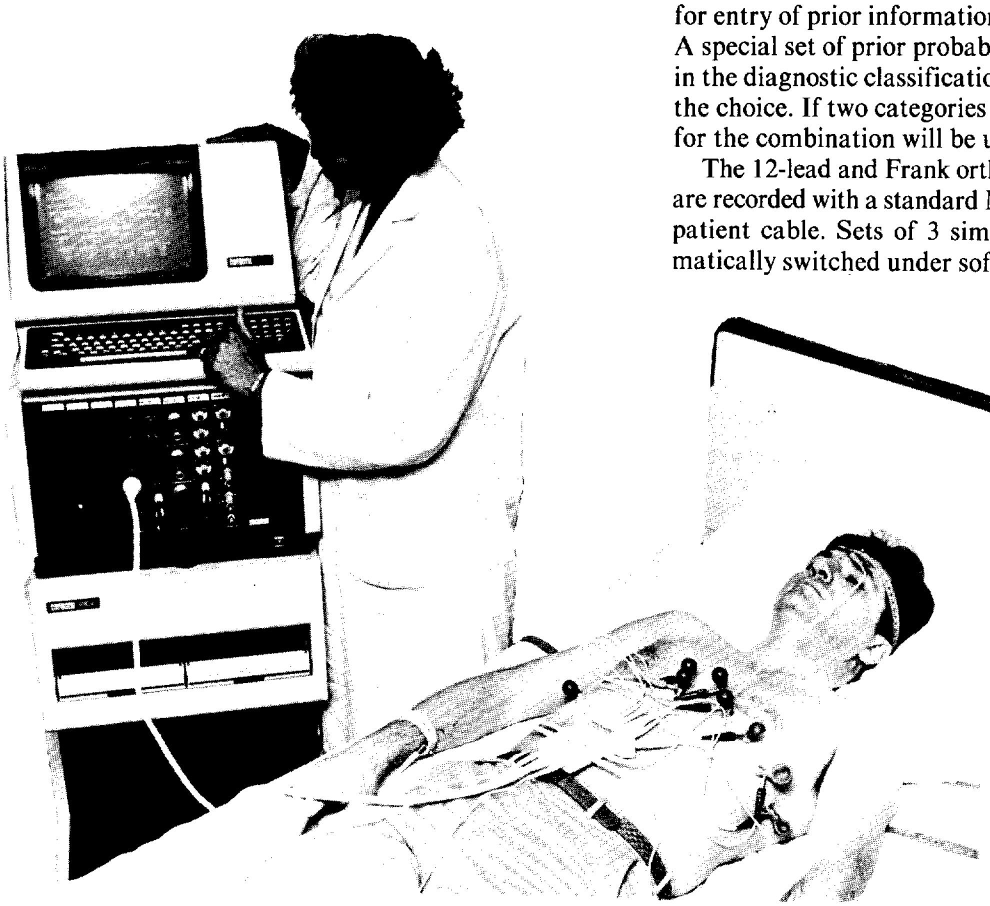

FIG. 1 Microcomputer-based ECG acquisition and analysis system.

TABLE I Diagnostic categories used for selection of the patient's tentative diagnosis for determination of prior probabilities

1. Normal cardiovascular status
2. Coronary artery disease
3. Hypertensive cardiovascular disease
4. Valvular or congenital heart disease
5. Pulmonary disease
6. Heart disease of unknown etiology
7. Preoperative

II III, aVR aVL aVF, V_1 V_2 V_3, V_4 V_5 V_6, calibration signals and XYZ leads. Two seconds of each 12-lead ECG and 6 seconds of the XYZ leads are converted to digital form at a sampling rate of 500 points/s and immediately displayed on the graphing terminal with the appropriate labels for visual inspection. The XYZ leads are then analyzed by the microcomputer and displayed on the screen with markers at the places where the computer has identified the features for calculation of the ECG measurements (Fig. 2). They are the onset and end of the P wave, the beginning and end of the QRS, and the end of the T wave. This display allows the technician or clinician to inspect the computer's identification of these features. There is an option to proceed to the measurement and diagnostic phases or record new data. Then a report is displayed which includes the diagnostic classification, rhythm analysis, and selected measurements (Fig. 3). Vector loops (Fig. 4) are also available. The results and the ECG tracings are stored on the floppy diskette. Comparisons with data and results previously recorded can be obtained immediately.

Wave Recognition

The wave recognition program locates the beginning and end of the P wave, the onset and end of the QRS, and the end of the T wave. Spatial velocities and magnitudes are calculated from the simultaneously recorded XYZ leads to transform the three leads into a single signal accentuating the distinguishing features of the ECG. Statistics from a large data base of normal and abnormal groups of ECG, where the important features had been visually identified by trained readers, were calculated for extensive use in the wave recognition program development. Ranges of spatial velocity and magnitudes are used first for locating the ECG waveforms. After the waveforms are located statistics are used to obtain the allowable windows for their onsets and ends. The actual onsets and ends are then determined by comparing the ECG's spatial velocity curves to templates for the beginning and end of the waveforms calculated from the large series of records. This program has been extensively tested and carefully checked. It has been shown that the variability of the computer wave recognition is reduced drastically as compared to human observers (Ishikawa *et al.*, 1971).

Measurements and Diagnostic Classification

The measurement program uses the landmarks identified by the wave recognition program to analyze and measure the waveforms. Approximately 200 measurements are calculated for each cycle in 6 seconds of recording. Prior to diagnostic classification the measurements for all cycles are entered into a statistical al-

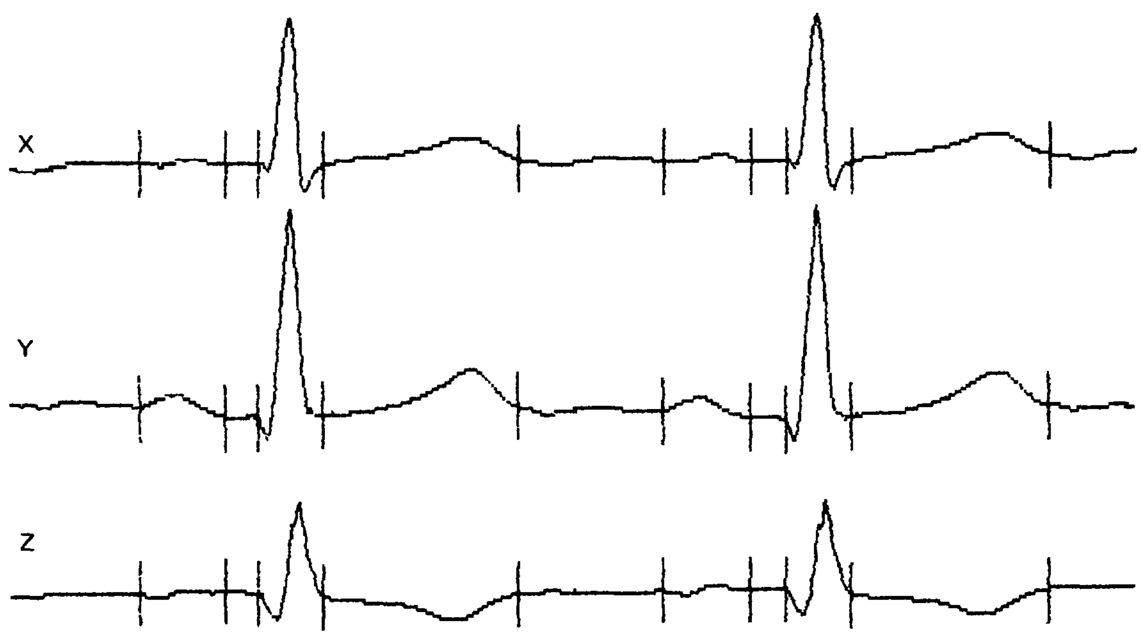

FIG. 2 Display of orthogonal lead electrocardiogram with markers at the places where the computer identified the features for calculation of the ECG measurements.

ECG REPORT

NAME: JOHN DOE ID: 123-45-6789 DATE: 10-08-81
BLOOD PRESSURE: 140/100 AGE: 46 RACE: WHITE

HEART RATE: 63/MIN NORMAL SINUS RHYTHM

QRS-T DIAGNOSTIC PROBABILITIES		P WAVE PROBABILITIES	
LEFT VENTRICULAR HYPERTROPHY	76 %	NORMAL	49 %
NORMAL	23 %	LEFT ATRIAL OVERLOAD	43 %

AMPLITUDES ARE GIVEN IN MILLIVOLTS, TIME IN SECONDS

P-DURATION	QRS-DURATION	P-R INTERVAL	QT RATIO
0.130	0.098	0.174	1.0

	Q-DURATION	R-AMPLITUDE	T-AMPLITUDE	POINT-J	Q/R RATIO	R/S RATIO
X	0.000	1.46	0.30	-0.00	0.00	5.06
Y	0.000	0.47	0.19	0.01	0.00	1.24
Z	0.041	1.15	-0.06	0.01	0.37	***

FIG. 3 ECG report containing the diagnostic classification, rhythm analysis and selected measurements.

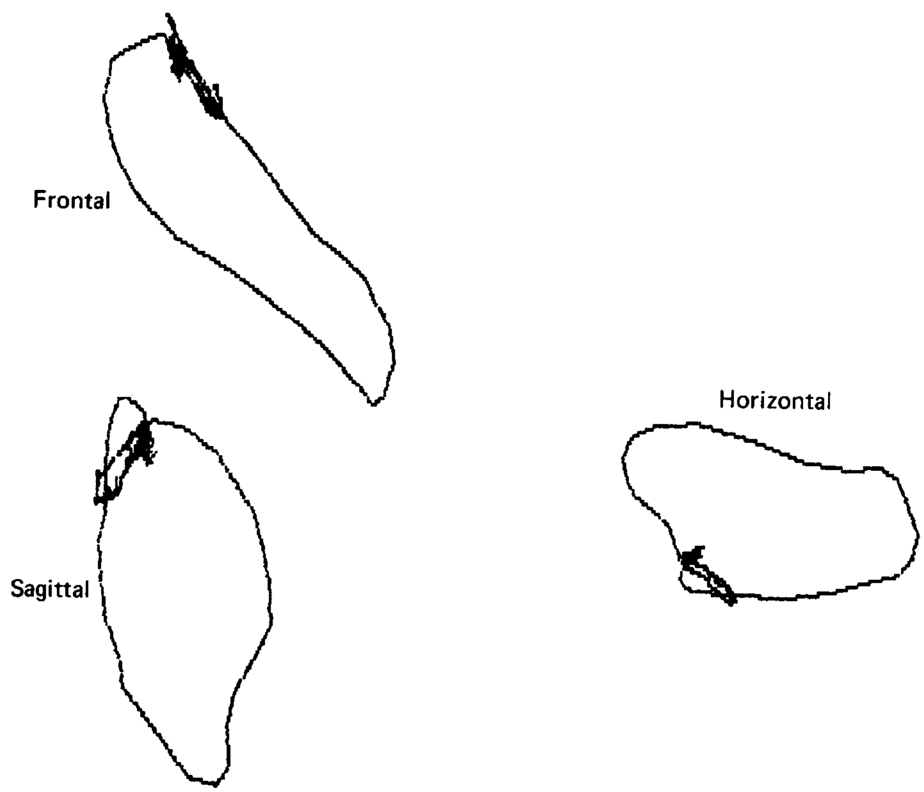

FIG. 4 Vector loops for the P, QRS, and T waves in the frontal, sagittal, and horizontal planes.

gorithm which tests for the reliability of the measurements. Measurements obtained from ectopic or aberrant cycles are eliminated and the remaining are averaged for use in classification. This procedure also eliminates measurements which are distorted by noise interference. Six-second record lengths allow efficient operation of the decision process with the number of beats depending on the heart rate.

The distinctive feature of the ECG analysis program is the application of a multivariate procedure (Cornfield *et al.*, 1973) in which large numbers of electrocardiographic measurements are used simultaneously for diagnostic classification. The results of the classification are diagnostic statements with posterior probabilities computed using a Bayesian approach. These probabilities indicate the likelihood that an electrocardiographic abnormality is present in a given record. The sum of the probabilities for all diagnoses being considered at one time equals one.

The posterior probability of a patient being in a particular disease group i from the m possible groups is by Bayes' theorem

$$P(i|\mathbf{x}) = \left[\sum_{j=1}^{m} \frac{g_j f(\mathbf{x}|j)}{g_i f(\mathbf{x}|i)}\right]^{-1}$$

where $\mathbf{x}$ is the vector of ECG measurements, g_i is the prior probability of being in disease category i and $f(\mathbf{x}|i)$ denotes the probability density function which is calculated from the patient's ECG measurements and statistics from the large well-documented patient data base. The prior probabilities are determined by asking the physician requesting the ECG to choose one or more of the broad diagnostic categories (Table I) as a tentative diagnosis. Different sets of priors are used for each choice or combinations of diagnoses.

This Bayesian classification procedure is used by the microcomputer to compute the patient's probabilities for the diagnostic categories listed in Table II. For ECGs not exhibiting a conduction defect, 66 QRS-T measurements are used in combination to compute the posterior probabilities for the first seven categories. If the probability of either type of hypertrophy is 70 percent or more, a conditional probability of biventricular hypertrophy is computed. In cases with ventricular conduction defect (QRS duration greater than 122 ms) records are classified in the categories 9–12 according to the ventricle involved and depending on whether a myocardial infarction is simultaneously present or not. The number of measurements used for this classification is 24. If a P wave is present and the measurements conform to certain standards, a probability of normal, right (RAO) and left atrial overload (LAO) is computed. Sixteen measurements are used for P-wave analysis. A separate analysis is made of the ST segment and T wave, resulting in statements relating to left or right ventricular strain, digitalis effect and myocardial injury.

Analysis of Cardiac Rhythm

This section of the program, which employs a decision-tree method for classification has been reported by Willems and Pipberger (1972) where the arrhythmia logic is described in detail. The most common arrhythmias are detected by simulating a cardiologist's "logic tree" approach. Ectopic beats and atrial fibrillation are the most common arrhythmias.

Results

This self-contained, microprocessor-based ECG system makes it possible to acquire and analyze ECGs in minutes. The system is user-friendly and any technician trained to record ECGs can operate this system with minimal instructions.

A key feature of the system is the display of the waveforms on the videographing terminal (Fig. 2). Vertical markers show where the computer has identified the important features. The accuracy of the identifications can be immediately verified by the technician or clinician. Vector loops (Fig. 4) are also displayed. These loops are in steps of 2 ms for the P, QRS, and T waves. Plotting can also be done for each wave separately. The user has a choice of different plot rates and of having the dots connected. Time interruptions can also be made.

The patient's diskette is updated by adding the results from the current recording. The data stored include the information entered through the keyboard, the calibrated orthogonal ECGs, the wave recognition results, the report which was displayed on the terminal, and all other measurements which were calculated. Since the ECGs and analysis results are stored on the patient's diskette, serial comparisons are readily available. Any results from a previous ECG recording can be retrieved for immediate visual inspection of any changes or trends. A hard copy of the waveforms or results displayed on the video screen can be obtained from a graphics printer.

The most important output of the system is the ECG diagnostic report. This report contains the results of the computer analysis and is displayed for immediate viewing on the 12 inch graphing terminal (Fig. 3). The first two lines of the report contain the patient information that was entered through the keyboard. The remainder displays the results of the computer analysis of the ECG: heart rate and rhythm analysis, the QRS-T and P wave diagnostic statements, and selected time and amplitude measurements. The appropriate diagnostic statements (Table II) are displayed together with the posterior probability for each statement. Posterior probabilities are calculated by multivariate analysis for all diagnoses under consideration. For each diagnostic category the probability can range from 0 to 100%, and the sum of the probabilities for all categories equals

TABLE II Diagnostic categories considered in computer analysis based on morphology of ECG

QRS-T wave categories if no conduction defect
1. Normal
2. Anterior myocardial infarct
3. Posterodiaphragmatic myocardial infarct
4. Lateral myocardial infarct
5. Chronic obstructive lung disease
6. Left ventricular hypertrophy
7. Right ventricular hypertrophy
8. Biventricular hypertrophy
QRS-T wave categories if ventricular conduction defect (QRS duration > 122 ms)
9. Left ventricular conduction defect
10. Left ventricular conduction defect with myocardial infarct
11. Right ventricular conduction defect
12. Right ventricular conduction defect with myocardial infarct
P wave categories
13. Normal
14. Left atrial overload
15. Right atrial overload

100%. Only the statements which have probabilities greater than or equal to 10% are printed. Probabilities greater than 70% have been found most reliable for diagnosis. A suggested diagnosis is indicated when they are between 40 and 70%. Probabilities for abnormal diagnoses below 40% should be ruled out. For example, for the report in Figure 3 the QRS-T probability of 76% for LVH is high enough to make a diagnosis of LVH. The P-wave probabilities of 49% normal and 43% LAO are very close, indicating that LAO should be considered but the diagnosis is less certain. Special diagnostic statements are printed if analysis of the ST and T waves have indicated the presence of such abnormalities. The time and amplitude measurements printed in the report are only a subset of approximately 200 measurements that are calculated for each cycle and can be displayed on the terminal.

It is interesting to note that one would not make a diagnosis of LVH on the basis of the measurements in the report of Figure 3 but that is not uncommon. Although the R amplitudes do not exceed the usual limits for normal and the T-wave measurements look normal, the computer arrived at the diagnosis of LVH through the use of a large number of other measurements. The patient on whom the ECG was made had a previous history of hypertension.

Validation of the software for this system has been supplied by several studies where diagnostic accuracy has been tested using independent evidence of patients' diagnoses (Brohet and Richman, 1979; Milliken *et al.*, 1983; Pipberger *et al.*, 1975). In one clinical trial (Pipberger *et al.*, 1975) computer analyses of more than 1192 orthogonal ECG records were compared with the "true" diagnoses of the patients, based exclusively on objective, independent information according to clinical protocols. The interpretations of 12-lead tracings performed by two well-known and experienced electrocardiographers were also compared with the "true" diagnoses. Of the total of 1192 records 86% were classified correctly by computer. In 5% the automated analysis was partially correct and 9% of the records were misclassified. Results of the 12-lead interpretations were 68%, 4%, and 28% for correct, partially correct, and incorrect classifications, respectively. Thus, an 18% increase in correct classifications was achieved by the application of the multivariate analysis. It is also significant that the number of misclassifications was reduced from 28 to 9%. Note that it is at least as important to minimize the misclassifications as it is to maximize the correct classifications in terms of trouble for the patient. The most striking differences between automated and conventional analysis were found in patients with hypertensive cardiovascular disease and chronic obstructive lung disease. In both groups computer results exceeded those obtained by conventional analysis by more than 50 percent.

In a more recent study Milliken and co-workers (Milliken *et al.*, 1983) evaluated the VA computer analysis program and its impact on the cardiologist's interpretation in a cooperative study. Again, the program was evaluated against ECG-independent evidence of 180 patients' true diagnoses. In addition, the impact of ECG computer reports on interpretation of nine experienced electrocardiographers was evaluated by comparing their interpretations before and after addition of a computer report to the 12-lead and orthogonal 3-lead ECG. Table III shows a comparison of the accuracy of the ECG diagnoses of the readers and the computer. The computer interpretation alone showed an average increase of 22% in accuracy of diagnosis when compared to the readers' diagnosis without benefit of the computer report. The superiority of the program was most striking for LVH where it showed a 36% improvement. Average accuracy

TABLE III Comparison of accuracy of ECG diagnosis of experienced electrocardiographers and computer against independent evidence of diagnosis[a]

Diagnostic entity	No. of cases	Accuracy of diagnosis (%)		
		Electrocardiographers	Computer	Difference
Normal	26	70	85	15
MI	65	65	77	12
LVH	61	41	77	36
RVH/COPD	25	36	56	20
BVH	3	74	100	26
	180	54	76	22

[a] Data taken from report by Milliken *et al.*, 1983

of ECG diagnosis of the readers increased by 8 percent when the computer report was added to assist them in making their diagnoses.

Results of evaluation of arrhythmia detection by the computer program have been reported by Willems and Pipberger (1972). Computer recognition is achieved in 90% of the cases for the most common arrhythmias. This percentage drops considerably when dealing with second or third degree heart block or other more uncommon arrhythmias. In the latter case, a statement "arrhythmia" is usually reported which is to alert the physician of a rhythm problem which might require therapeutic intervention.

Discussion

Our reason for developing this system was to combine the most advanced ECG diagnostic software with advances in hardware based on state-of-the-art microprocessors. Until recent advances in microcomputers it was impossible to run a large, sophisticated analysis program such as the Veterans Administration's on a portable system. It is especially remarkable that this complete, stand-alone system is more economically feasible than systems requiring telephone transmission of the ECG signals and return transmission of the report. The fidelity of the tracings which are transmitted directly from the patient to the computer by a standard ECG cable is far superior to the fidelity obtainable with telephone transmission. This self-contained, microcomputer-based system is easy to use and allows interaction between the technician and the system encouraging better quality recordings.

The software used in this system has been under development since the VA cooperative study, comprising eight hospitals, was organized in 1960 for data collection (Pipberger, 1966). The orthogonal Frank-lead and 12-lead ECGs were recorded on each patient who satisfied strict protocol criteria. The patients were classified into diagnostic categories, based exclusively on independent, that is, non-ECG, information such as cardiac catheterization data, autopsy reports, etc. Approximately 30,000 records were collected, providing the data for development and testing. Over 300 measurements were made on each cycle of the ECGs in the Veterans Administration's large well-documented data base. Virtually every ECG variable that has been suggested in the electrocardiographic literature was included. Statistics were compiled on the measurements from these well-documented records to determine the parameters which best characterized a disease group and which best discriminated between disease groups (Eddleman and Pipberger, 1971; Gamboa *et al.*, 1969; Kerr *et al.*, 1970). These large amounts of data were essential for development and rigorous testing of the wave recognition and diagnostic classification techniques.

The importance of the wave recognition was emphasized because any computer diagnosis is dependent on accurate wave recognition. For a computer program to be clinically useful the wave recognition must not only be consistent but correct. The wave recognition program was developed by using statistics calculated from a large number of records in which the important features had been visually identified by trained readers. Thus, the program was made to identify the features as a trained electrocardiographer would. Continued development and testing on new records insured that the algorithms used are sophisticated enough to accurately identify almost any waveform configuration.

An important capability with the new system is the option to review the computer's identifications on the video terminal (Fig. 2). When the waveform identifications are made accurately the measurements calculated from these identifications can be relied upon with confidence. To reduce the effects of noise and physiological factors the system uses records of sufficient length to calculate the measurements for many cycles. Measurement variation is significantly reduced by eliminating ectopic or aberrant beats and averaging those remaining. This technique and the use of simultaneous leads eliminate the problems which occur in systems which record only one lead at a time or lead sets that have insufficient numbers of cycles for statistical analysis.

The multivariate classification program for diagnosis which applies Bayes' theorem explains the improvement in diagnostic classification. Applications of Bayes' theorem for diagnostic classification are becoming increasingly widespread (Wagner, 1982). Use of Bayes' theorem in the ECG program is particularly successful because of the availability of the Veterans Administration's very large data base consisting of records from patients with firmly documented diagnoses. Many measurements from each patient's ECG are simultaneously used with the statistics from this large data base to obtain the patient's classification. The use of appropriate prior probabilities in the Bayesian classification procedure proved to be a highly significant factor in diagnostic accuracy. In a formalized statistical sense this procedure may appear new or even strange to the physician. However, it represents a procedure that is quite familiar to every clinician because he uses this approach whenever he is faced with a diagnostic problem, i.e., using prior information he has about the patient to help in making his diagnosis. Physicians' acceptance of computer results in the form of probabilities has been gratifying. This is probably because in all problem cases, various possible diagnoses are considered with a certain likelihood. In addition, in cases with left or right ventricular hypertrophy, the probability levels have been found a useful indicator for the degree of hypertrophy that may increase or decrease in time as shown in follow-up tracings.

The most frequently used measures of performance for computer analysis of ECGs are reproducibility and diagnostic accuracy. In experiments on reproducibility by Bailey and co-workers (Bailey *et al.*, 1976) the Veterans Administration program showed the least variability of all programs tested. The program with the next best reproducibility had changes in diagnostic statements in 30% of the cases tested (Bailey and Horton, 1979). If a user is to have any confidence in a given program, then it must give essentially the same answer for a patient whose ECG is essentially unchanged.

Evaluation of diagnostic accuracy can be performed in a variety of ways. Most designers of programs for computer diagnosis of ECGs had to make an individual and arbitrary selection of diagnostic decision rules which were considered optimal by them but not necessarily by others. Almost without exception, performance tests were done by program designers themselves using the same decision rules. As expected, "diagnostic accuracy" of such evaluations varied between 80 and 95%. That there was any failure rate had to be attributed to technical errors in wave recognition or measurement programs. Since the same diagnostic rules were followed both by the computer and the human reader, it is clear that "diagnostic accuracy" is not tested at all in such studies.

Comparisons between results obtained by a given computer program and results of human ECG interpreters who may use their own diagnostic rules have been less frequently applied. As could be expected, percentages of disagreement rose sharply and reached almost 50% in one report (Caceres and Hochberg, 1970). Failure of agreement was attributed to a variety of sources, such as technically poor recordings, physician error, imprecise measurements, differences in opinion, and imprecise criteria. Considering the accuracy rate of slightly more than 50% obtained by expert electrocardiographers in the cooperative study by Simonson *et al.* (1966), one may wonder about the real meaning of such a comparison.

Both the American Heart Association and the American College of Cardiology recommended, many years ago, evaluation of ECG computer programs only against independent evidence of diagnosis. The Tenth Bethesda Conference on Optimal Electrocardiography (Rautaharju *et al.*, 1978) calls for accuracy to be "evaluated by using a library of cases for which the diagnosis is determined or excluded by nonelectrocardiographic means." Evaluations where these recommendations have not been used are of limited value because of bias introduced by observers or evaluators (Pipberger and Cornfield, 1973). While this recommendation has not been followed for evaluation of other systems, the diagnostic performance of the Veterans Administration program has been extensively tested against independent evidence for the diagnoses and found to be quite satisfactory and reliable (Brohet and Richman, 1979; Milliken *et al.*, 1983; Pipberger *et al.*, 1975). It is fortunate that these evaluations against independent evidence do exist. The results of these studies all showed that the diagnostic accuracy rate of the computer program was significantly higher than the rate achieved by expert electrocardiographers. Thus they strongly suggest that diagnostic ECG classification can be significantly enhanced through the use of multivariate analysis.

The ECG diagnostic software used in this new system has undergone extensive development and testing and is a well-established computerized ECG program. The application of this software to a small, mobile microcomputer is new and now makes it possible for clinicians to utilize the ECG diagnostic software in a complete, stand-alone system that is ready and practical for use in a doctor's office, clinic, or small hospital.

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